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Die Attachment for −120°C to +20°C Thermal Cycling of Microelectronics for Future Mars Rovers – An Overview

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ABSTRACT

Active thermal control for electronics on Mars Rovers imposes a serious penalty in weight, volume, power consumption, and reliability. Thus, we propose that thermal control be eliminated for future Rovers. From a functional standpoint there is no reason that the electronics could not operate over the entire temperature range of the Martian environment, which can vary from a low of ≈−90°C to a high of ≈+20°C during the Martian night and day. The upper end of this range is well within that for conventional electronics. Although the lower end is considerably below that for which conventional—even high-reliability—electronics is designed or tested, it is well established that electronic devices can operate to such low temperatures. The primary concern is reliability of the overall electronic system, especially in regard to the numerous daily temperature cycles that it would experience over the duration of a mission on Mars.

Accordingly, key reliability issues have been identified for elimination of thermal control on future Mars Rovers. One of these is attachment of semiconductor die onto substrates and into packages. Die attachment is critical since it forms a mechanical, thermal and electrical interface between the electronic device and the substrate or package. This paper summarizes our initial investigation of existing information related to this issue, in order to form an opinion whether die attachment techniques exist, or could be developed with reasonable effort, to withstand the Mars thermal environment for a mission duration of approximately 1 year.

Our conclusion, from a review of literature and personal contacts, is that die attachment can be made sufficiently reliable to satisfy the requirements of future Mars Rovers. Moreover, it appears that there are several possible techniques from which to choose and that the requirements could be met by judicious selection from existing methods using hard solders, soft solders, or organic adhesives.

Thus, from the standpoint of die attachment, it appears feasible to eliminate thermal control for Rover electronics. We recommend that this be further investigated and verified for the specific hardware and thermal conditions appropriate to Mars Rovers.

Introduction and Background

Mars Rovers, like most other spacecraft, use active thermal control to maintain the electronics within "traditional" temperature limits. Eliminating this thermal control would provide several major benefits: (1) reduced launch weight and volume of the payload (directly as well as indirectly from reduced power consumption and control requirements), (2) enhanced maneuverability of the Rover, (3) enhanced operating life and reliability of the Rover, (4) reduced overall cost. Use of passive rather than active thermal control is possible, but this would still result in a weight and volume penalty; moreover, passive control might be unable to maintain the electronics within the desired temperature range. Thus the best solution seems to be adoption of electronics that can withstand the entire Mars environmental temperature range.

It has been extensively demonstrated that electronics can operate over the entire temperature range seen by a Mars Rover and beyond. There is considerable experience with many types of electronic components and subsystems for low temperatures:

- Spacecraft: The Infrared Astronomical Satellite, Infrared Space Observatory, Infrared Telescope in Space, and others used electronics operating at cryogenic temperatures (≈−150°C and below) and additional spacecraft are planned that incorporate cryogenic electronics.

- Computers: ETA built computers with Si ICs operating in liquid nitrogen (−196°C); IBM developed packaging and interconnections for a Josephson-junction computer to operate at liquid-helium temperature (≈−269°C).

- Microwave receivers: the Deep Space Network and radio astronomy receivers use semiconductor electronics operating at ≈−260°C.

- Signal-processing systems: readout electronics for particle physics instrumentation operates at liquid-argon temperatures (≈−186°C) and below.

- Infrared arrays: complex readout ICs coupled to infrared detector arrays operate at a variety of cryogenic temperatures.

This experience demonstrates the ability of electronics of many types to operate at low temperatures, easily covering the Mars Rover range. Regarding reliability, a General Electric group mentions that multi-chip modules survived 1000 cycles between −200°C and +155°C (Daum et al. 1993, Fillon et al. 1995). However, for most of the applications listed above the number of temperature cycles is much fewer. Also, formal low-temperature reliability data are scarce.

Thus, eliminating thermal control for electronics on the Rover, or for other spacecraft electronics, becomes a matter of establishing the required reliability for the electronics. In regard to packaging and interconnections, two critical areas have been identified (Kolawa and Sokolowski 1998):

- Flexible cabling (thermal cycling plus mechanical flexing at low temperatures),

- Die attachment of semiconductor devices onto substrates and into packages (thermal cycling) (Brandon 1997).

This paper addresses the latter of these, die attachment, relative to low temperatures and thermal cycling to low temperatures. It summarizes an initial phase—gathering available information from literature and personal contacts, and outlining provisional conclusions and recommendations. So far, over one hundred technical papers, reports, and books have been examined, and of these approximately half (included in the references) have data relevant to low-temperature die attachment. Also, so far, approximately two dozen persons have been contacted for relevant information and experience.

The key outcome from reviewing available information is that there appear to be die attachment materials and techniques, reasonably practical, that can be used for the required Mars Rover temperature range, which includes temperatures much lower than the usual –55/–65°C. There have been a number of experimental investigations on materials and techniques relevant to die attachment for low temperatures, as summarized in Table 1.

However, the available data are for assemblies that were cycled at most hundreds of times from room temperature to cryogenic temperature. The proposed requirement for the Mars Rover is somewhat different—thousands of temperature cycles over a smaller temperature range. Thus further work is needed to verify die attachment for Mars Rovers.

Materials Choices for Die Attachment

Materials used for die attachment may be grouped into four categories: "soft" solders, "hard" solders, organic adhesives, and inorganic adhesives. These are considered below in regard to electronics that will be exposed to low temperatures. Most information found during this investigation relates to the "soft" solders.

(1) "Soft" solders: Examples include PbSn, InSn, and InPb alloys (M.P. ≈150–300°C). Compared to the "hard" solders, these solders have the advantage of lower assembly temperatures during die attachment, particularly low-melting alloys such as In52Sn48 (M.P. 118°C) or In51Bi33Sn16 (M.P. 61°C). However, they tend to relax under stress, and repeated temperature cycling can lead to failure. Behavior differs greatly among the alloys; some general trends may be extracted from the experimental reports:

"Soft" solders typically increase in strength and decrease in ductility with decreasing temperature (Ainsworth 1971, Jaffee et al. 1948, Jones et al. 1996a/1997a/1997b, Liu et al. 1996, Reichenecker 1982). This remains generally true down to cryogenic temperatures, –196°C (77 K) and –269°C (4 K) (Fast et al. 1988, Mruzek 1980, Nyilas and Zhang 1990, Plötner et al. 1991). Pb-rich PbSn alloys retain a fair fraction of their ductility down to cryogenic temperatures; however, as Sn content increases, particularly for >≈40% Sn, PbSn alloys become brittle below ≈–50°C to ≈–150°C (Jones et al. 1996a/1997a/1997b, Kalish and Dunkerley 1949, Liu et al. 1996, MacIntosh 1968, Reichenecker 1982). Thus there is a serious question whether Sn-rich PbSn solders would be advisable for Mars Rovers.

Several persons contacted said that their experience showed that adding a small amount of Sb to Sn-rich solders avoids the problem of low ductility at low temperatures. SnPbSb has been used extensively for cryogenic wind tunnel instrumentation. Reports of low-temperature testing, although scant, also tend to indicate that SnPbSb is useable down to cryogenic temperatures (Firth and Watkins, Jr. 1986, Hall 1986). On the other hand, Reichenecker's (1982) measurements of Sn40Pb58Sb2 (as well as SnSb, SnAg and SnPbNi alloys with a high percentage of Sn) show a drop in ductility below ≈–50°C similar to that of Sn-rich SnPb alloys. Yoshioka et al. (1990) measured a Sn-rich solder with 2% Ag and found that although its ductility decreased at low temperature its fatigue life did not decrease.

Tong et al. (1989a/1990/1993) found that a polymer coating doubled the life for cycling PbSn bump bonds to –196°C.

The advantage of using indium and indium alloys for cryogenic joining has been appreciated for many years. Their greater ductility (Plötner et al. 1991/1991a) and longer lifetime (Hashimoto 1991/1992, Yamamoto 1991) have been demonstrated, especially for pure In, compared to standard PbSn solders at cryogenic temperatures. Hashimoto et al. (1991/1992) suggest the elongation-to-strength ratio as an indicator of fatigue life. Adding other elements can further improve low-temperature ductility (Jones et al. 1997) or fatigue life (Yeh 1982).

(2) "Hard" solders: Examples include AuSn, AuGe and AuSi alloys (usually eutectic). These have higher melting temperatures (M.P. ≈300–400°C), and are often called *brazes* in the microelectronics community. These materials do not undergo stress relaxation at ordinary electronics temperatures, but as a consequence may transmit more stress to semiconductor die provoking cracks in the die. The high temperatures required for die attachment would also aggravate stress when assemblies are cooled to low temperatures.

We have not located any low-temperature mechanical data for these alloys, except that of McNeil (1963), who found that the hardness of the AuSn intermetallic compounds increases with decreasing temperature.

In regard to low-temperature electronics, a University of California Irvine group reports success in using AuSn to attach both Si and GaAs die to alumina. During cycling between –196°C and +160°C for up to 40 cycles for Si die (Matijasevic et al. 1990/1990a) and up to 100 cycles for GaAs die (Lee and Matijasevic 1989, Matijasevic and Lee 1989) they saw no degradation, so conceivably the die attachment could withstand many more cycles.

(3) Organic adhesives: These include epoxies and polyimide adhesives, usually filled with metal (such as silver) or dielectric (such as alumina) powder. Low-temperature physical properties and cycling data are scarce, but there are a few reports of epoxies used successfully for low-temperatures with standard die attachment (Chen et al. 1990, Goldfarb et al. 1982/1985). We have found no data on polyimides at low temperatures as yet. There are also newer thermoplastic adhesives, but likewise no low-temperature data have been found for these.

(4) Inorganic adhesives: The primary example is silver-glass. We have found no low-temperature data for this category of materials as yet.

Temperature Cycling

Temperature range and number of cycles: For the purposes of this task we have adopted a temperature range of –120°C to +20°C, to provide a safety margin on the low end. The baseline Rover operation life is a minimum of one Earth year. A Martian day is about the same length as an Earth day, and thus the Rover electronics would experience about 360 temperature cycles minimum. The proposal is to qualify the electronics for an order-of-magnitude greater number of temperature cycles—several thousand cycles. As mentioned, this is considerably greater than existing experience for low-temperature electronics. The electronics would also need to withstand exposure to temperatures up to +50°C several times for qualification thermal-vac or bake-out treatments.

Stress and strain in die bonds from temperature effects (such as cycling) are related to three factors:

- Size, specifically the greatest length over which materials are joined, ΔL,

- Differences in coefficient of thermal expansion (CTE), ΔCTE, between joined materials,

- Temperature extremes or temperature differences, ΔT.

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Table 1 – Guide to low-temperature/cryogenic information in references. *Notes:* RT = room temperature; ● = some information, ●● = more information.

Materials	Temperature (°C)	Thermal cycling	Mechanical properties	Fracture/ interface analysis	Thermal/ mechanical modeling	Coefficient of thermal expansion	Other	References
					"Soft" Solders			
Sn, SnPb, SnSb, PbSnAg	-250 to +200		●●					Ainsworth 1971
In	-196 to RT	●●					CTE of substrate and chips	Aoki et al. 1992/1992a
InSn	-269 to -196		●●	●●				Caulfield et al. 1984
Pb, Sn, PbSn	-269, -196		●●				Electrical resistivity	Fast et al. 1988
InBiSn	-269 to RT	●	●●	●			Fluxes, joint resistance, phase structure	Fujiwara et al. 1987, Fujiwara and Asahi 1987a
In, InPb, InSn, SnPb	-196 to RT	●●	●●				Wetting, power cycling, joint resistance	Hashimoto et al. 1991/1992
PbSn, PbAg, PbSnAg	-182, -59, -29, RT		●●					Jaffee et al. 1948
SnPb, SnPbAg, SnAg	-200 to +150		●●					Jones et al. 1996/1996a/1997a/1997b
InSn, InSnAg, InSnAgZn, InSnZn, InPb	-200 to +100		●●					Jones et al. 1997
SnPb	-196 to RT		●●					Kalish and Dunkerley 1949
PbSn, PbSnAg, SnAg	-200 to +150		●●	●●				Liu et al. 1996
PbSn	-269		●					Mruzek 1980
SnPb, SnPbAg, SnAg, InPb	-269		●●					Nyilas and Zhang 1990
PbSn, SnSb, SnAgSb	-150 to +200		●					Olsen and Berg 1979
In, InBi, InBiSn, InSn, PbSn	-196, RT		●●					Plötner et al. 1991/(1991a)
InSn	-269, -196		●				Microstructure	Purushothaman and Caulfield 1984
In	-269, -263, -197, RT		●				Microstructure	Reed et al. 1988
In	-269, -197						Creep	Reed and Walsh 1992
Sn, SnPb, PbAg, PbAgIn, PbAgSn, SnAg, SnSb, PbIn, PbAgSb, SnPbSb, SnPbNi	-130 to +150		●●					Reichenecker 1981/1982/1983
In	-273 to RT		(●)			●	Electrical resistivity	Swenson 1955
InBiSn	-269	●	(●)	●			Microstructure, joint resistance	Ting et al. 1982
PbSn	-196 to RT	●		●	●●		Joint resistance	Tong et al. 1989/1989a/1990/1993
In, SnPb, InSn, InPb	-196 to RT	●			●		CTE of substrate and chips	Yamamoto 1991
InBiSn, InSn	-196 to RT	●	●●	●●			Microstructure	Yeh 1982/1984
PbSnAg	-140, -100, RT	●	●		●		Fatigue	Yoshioka et al. 1990
					"Hard" Solders			
AuSn	-196 to +135/+160	●	●●	●●				Lee and Matijasevic 1989, Lee et al. 1991, Matijasevic and Lee 1989/1989a
AuSn	-196 to +160	●	●RT only	●●		●	Low- and high-temperature storage	Matijasevic et al. 1990/1990a
AuSn	-196 to +262						Data for intermetallic compounds only	McNeil 1963
AuSn, AuGe, AuSi	-80 to +180		●					Olsen and Berg 1979
					Organic Adhesives			
Epoxies (cond. & insul.)	-138 to RT	●	●RT only			●		Chen et al. 1990/1990a
Epoxy (cond.)	-196				●●	●		Ulrich and Rajan 1993/1995/1996/1996a

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It is preferable to minimize each of these factors. The first, size, is subject to the same considerations as for conventional electronics, and will not be discussed here. The second and third are discussed below in relation to the temperature range of the Mars Rover.

CTE differences: For illustration, CTE data for four materials used in microelectronics are plotted over the temperature range of interest in Figure 1. Since the die will likely be silicon or possibly gallium arsenide, the substrate CTE should be considered relative to the CTEs of these two die materials.
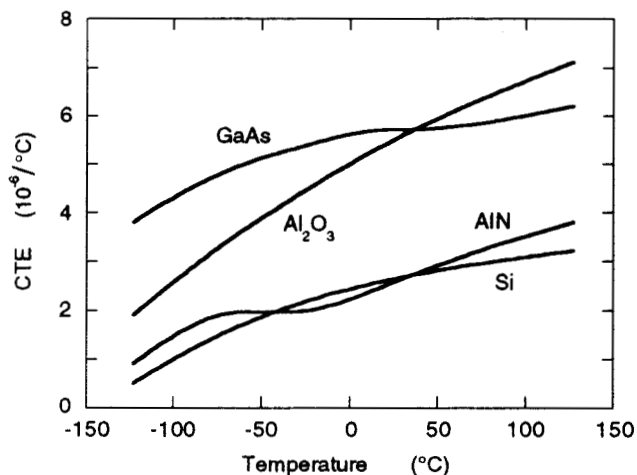
Figure 1 - Coefficient of thermal expansion (CTE) for four materials used in microelectronics: silicon (Si), gallium arsenide (GaAs), alumina (polycrystalline Al_2O_3), and polycrystalline aluminum nitride (AlN) (Touloukian 1975/1977).

Si: The most common substrate material, alumina, does not match particularly well to Si; even so, several groups have reported success for Si die attachment to alumina over the required temperature range. Hashimoto et al. (1991/1992) used "soft" solders and flip-chip mounting; presumably the solders released stress during thermal cycling, in accord with the longer lifetime of the more ductile solders. Tong et al. (1989/1989a/1993) were also successful in flip-chip mounting using a "soft" solder. On the other hand, Matijasevic et al. (1990/1990a) were successful using a "hard" solder and standard (not flipped) die attachment. Aluminum nitride (AlN) has a better CTE match to Si than does alumina; however, we have found no data on die attachment to AlN for low temperatures. The best CTE match for Si is Si itself and several groups have used Si substrates, demonstrating successful die attachment over the required temperature range using "soft" solders (Fujiwara et al. 1987, Ting et al. 1982) or epoxy (Chen et al. 1990/1990a, Goldfarb et al. 1982/1985).

GaAs: Two groups report successful die attachment for GaAs to alumina: for flip-chip with "soft" solders (Hashimoto et al. 1991/1992), and for standard attachment with a "hard" solder (Lee and Matijasevic 1989, Lee et al. 1991, Matijasevic and Lee 1989). The CTE match for GaAs to alumina is better than that for Si to alumina, consistent with the longer life of GaAs soft-solder flip-chip bonds reported by the first group (Hashimoto et al. 1991/1992). Aoki et al. (1992/1992a) developed a special ceramic (alumina-treated zirconia plus borosilicate glass composite) for an improved CTE match to GaAs die and thereby obtained superior

lifetimes compared to alumina substrates for soft-solder (In) flip-chip attachment cycled to –196°C.

These results suggest that certain materials and techniques can be used successfully for die attachment for the required Rover temperature range. Both "soft" and "hard" solders are candidates. However, these results are for only several hundred or fewer temperature cycles and further work would be needed to confirm suitability.

It should be borne in mind that even with perfect CTE matching there are unavoidable thermal expansion stresses due to temperature gradients. These arise from heat flow and differences in heating and cooling during the environmental temperature changes and due to power dissipation and power cycling. Such gradients can be reduced through good thermal conduction. In addition, insulation and heat "sinking" (thermal inertia) might be used to reduce temperature excursions and rate of change.

Temperature extremes: For most materials CTE decreases as temperature decreases, as illustrated in Figure 1 for the four materials used in microelectronics assemblies. Thus the lower temperatures for the Rover range work to our advantage. For example, Figure 2 compares the differences in thermal expansion ($\Delta L/L$) for silicon and alumina over the Rover temperature range. The vertical line at –120°C labeled "R" is the expansion difference for the proposed Mars Rover range of –120°C to +20°C, and the sum of the two vertical lines at –55°C and at +125°C gives the expansion difference for the "military" range of –55°C to +125°C. Numerical values are given in Table 2 and show that the difference in expansion for the Mars Rover range is about half that for the military range. This is partly due to the slightly smaller range for the Rover ($\Delta T = 140$°C versus 180°C) but primarily due to the lower CTEs over the lower temperature range for the Rover.
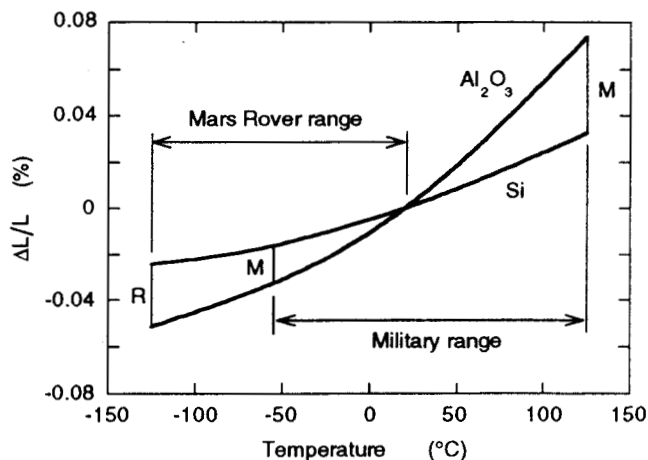
Figure 2 - Differences in thermal expansion ($\Delta L/L$) for Si and alumina, normalized to room temperature (20°C).

Thus, on this basis, the Mars Rover range would result in less stress than the often-used "military" range. The existence of high reliability electronics for the "military" range implies that the same can be made for the Mars Rover range. However, there remains the question is how the materials act under the influence of this stress, specifically how they might act differently over the lower temperature range in regard to microstructural reorganization.

In addition, the temperature used during die attachment (specifically the solidification temperature of the alloys or adhesives) must also be considered. Since the zero-stress point is

"frozen in" at this temperature, there is some "built-in" stress even at room temperature when the assembly cools. Thus, it would be preferable to use the lowest possible assembly temperatures for the Rover. Materials that produce a bond at a low temperature but that retain their integrity to a higher temperature might be used, for example a two-part room-temperature-curing epoxy or certain metal systems used in soldering.

Table 2 - Comparison of differences in thermal expansion (ΔTE) for alumina and silicon (numerical data corresponding to Figure 2).

Mars Rover Range −120°C to +20°C (ΔT = 140°C)	
ΔTE at −120°C	0.027%
ΔTE at +20°C	0%
ΔTE −120 to +20°C	**0.027%**
Military Range −55°C to 125°C (ΔT = 180°C)	
ΔTE at −55°C	0.017%
ΔTE at +125°C	0.038%
ΔTE −55 to +125°C	**0.055%**

Conclusions and Recommendations

From this initial phase of investigation it appears that die attachment can be made sufficiently reliable to satisfy the requirements of future Mars Rovers. Existing experience indicates that there are several candidate materials systems and techniques, including hard solders, soft solders, and organic adhesives. Thus, from the standpoint of die attachment, it appears feasible to eliminate thermal control for Mars Rover electronics.

However, the proposed Rover qualification represents a situation outside existing experience: neither guidelines nor technology have been established for the proposed thousands of cycles over the Mars temperature range. Thus, the selected die attachment technology would need verification under the appropriate conditions. The situation is not straightforward because many factors affect the results, and the conditions in previous investigations are different from those for the Mars Rovers. This underscores the need for appropriate qualification.

Hard solders appear to be a primary die-attach candidate for investigation because of their resistance to microstructural evolution. In particular, eutectic AuSn (Au80Sn20) is the lowest-melting of the common hard solders and has been shown to produce bonds that remain good after cycling to low temperatures (Lee and Matijasevic 1989, Lee et al. 1991, Matijasevic and Lee 1989, Matijasevic et al. 1990/1990a). Furthermore, eutectic AuSn is a standard die attachment material compatible with normal microelectronic assembly.

In-alloy solders might also be a good choice for the large number of temperature cycles for the Rover; however, they may not be necessary for −120°C (not quite into the cryogenic range of <≈−150°C). "Traditional" PbSn alloys, or slight modifications thereof, could be adequate, although Sn-rich alloys warrant caution.

Investigation of alternative substrate materials for better CTE matching to Si also appears worthwhile (AlN for example, which also has high thermal conductivity) as well as evaluation of epoxy and polyimide adhesives with regard to temperature cycling life.

In addition to mechanical testing (die-shear), electrical resistance and thermal conductivity tests should be a part of any evaluation to determine die attachment quality. Acoustic and x-ray

evaluations for bond integrity should be used. In particular, die attachment materials meant to be electrically conductive, such as silver-filled epoxy or silver-glass can potentially become non-conductive or less conductive at low temperatures or after temperature cycling. This possibility needs to be evaluated experimentally. Similar concerns apply to thermal conduction of die attachment materials, which may be degraded by temperature cycling.

Finally, development of reliable electronics for future Mars Rovers will require a comprehensive approach including many factors in addition to those addressed here. The entire die-attachment system must be considered—the die, die attachment materials, substrate, and any metallizations, coatings, encapsulations, etc. The characteristics and influence of all of these must be taken into account. Also, the interrelation of die attachment materials with thermal conduction, power dissipation, heat distribution and overall thermal design of the Rover must be considered

Additional information resulting from this phase of our investigations is available in a JPL report.

Acknowledgments

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